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Photographic Investigation of the Projection of Droplets by Bubbles Bursting at a Water Surface.

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ABSTRACT

Bubbles of air on reaching the air-water interface burst and eject liquid droplets into the air to heights large compared to their diameter. Photographic evidence is introduced to prove the existence of a jet of liquid which, upon breaking up, produces these droplets. The jet is shown to be produced by the collapse of the bubble cavity.

The droplets are found to be nearly one tenth of the bubble size for the range investigated (0.2 to 1.8 mm. diameter).

The droplet producing mechanism is essentially the same for fresh and sea water or sea water with oleic acid surface film. The time required for the bubble to burst and the jet formation to take place is found to be proportional to the bubble size. The sea water droplets produced by this mechanism leave, upon evaporation of the water, salt nuclei having the size range observed by Woodcock (1952).

It is suggested that such bursting of bubbles plays an important role in the natural production of air-borne sea-salt nuclei at the sea surface.

I Introduction

Among meteorologists it has long been recognized that air-borne chloride particles may play an important role in fog, cloud and precipitation processes.

Kinch (1887) and many other workers, at widely different geographical locations, have found chloride in rain waters. Köhler (1936) and Houghton and Radford (1938) measured chloride in cloud and fog waters which they attributed to the presence in the air of sea-salt nuclei on which the cloud and fog droplets formed. Owens (1926) measured the sizes of some of the larger salt particles found in clear air near the sea surface, and Woodcock (1952) extended the range of salt particle size measured and showed that these particles are also present in clear air at cloud levels. It is the purpose of the present study to show that the mechanism of the bursting of small bubbles at the sea surface can account for the initial introduction of sea-salt nuclei into the air.

All of the above authors recognized that the sea surface was the source of the chlorides measured. Köhler (1941) proposed that the formation of spray at wave crests by strong winds was responsible for air-borne salt nuclei. Facy (1951) suggested that rupturing of bubble films produces the observed weights of nuclei. Stuhlman (1932) had previously suggested that the bursting of bubbles in distilled water produced jets (similar to "Worthington's Splashes") which broke into small droplets. The present study proves that jets occur when small bubbles burst at the surface of fresh water and sea water. It is shown that the jets formed in sea water can account for a large portion of the range of weight of the salt particles observed in the free air. The relative percentage of the naturally occurring salt nuclei which originate from the breakup of jets and from other mechanisms remains to be investigated. High speed photography has been the primary tool in carrying out the present study.

II Photographic Observation of Bursting Bubbles

As previously pointed out, Stuhlman (1932) has suggested that the formation of a jet on the bursting of a bubble is the principle mechanism by which droplets are ejected into the air. In this investigation bursting bubbles (diameter 0.2 to 1.8 mm.) in fresh and sea water were photographed from above and below the surface, in an effort to show in more detail the mechanism proposed by Stuhlman.

Figure 1 shows still photographs (less than 30 microseconds exposure time) of one millimeter bubbles bursting in fresh water. The sequence has been established by comparison with high speed motion pictures. These photographs were made in an unsuccessful attempt to observe the rupture of the bubble surface film. The exposure time was much too long to stop this exceedingly rapid phenomenon. It is significant, however, that no droplets of large enough size to be resolved by the film and optical system were observed from bubbles of this size until after the jet formation. This is thought to indicate that the larger droplets are not produced when the bubble film is broken.

The initial burst of the bubble is observed as a slight wave train starting outward. The cavity widens until it is almost twice the initial size. The jet suddenly projects upward, continues to rise as a thin column, and then the unstable column breaks into droplets of varying size. In general, the last droplet to leave the jet has very little vertical motion and rapidly returns to the surface. The jet finally collapses completely, and the surface where the jet action occurred becomes completely smooth, without further oscillation.

The horizontal views in Figure 2 show the collapse of the cavity prior to the formation of the jet. The four sequences indicate how a jet forms from a conical depression which, in turn, is formed from the initial spherical cavity. In the time interval from the initial rupture of the film until the depression has assumed a conical shape, a disturbance (probably associated with the drawing back of the upper lip of the cavity by surface tension) is observed to propagate downward from the surface.

Figure 2 strongly suggests that the dynamics of the jet, the size of projected droplets, and the height reached by the droplets are determined by the shape and hydrodynamics of collapse of the cavity itself. Very large mass velocities are probably associated with the converging flow at the vertex of the cone. The extremely rapid withdrawal of the lip of the cavity, considerably prior to formation of the jet, leaves little foundation for Stuhlman's (1932) proposed mechanism of jet formation under a "sucking" influence of a vortex ring formed by the ejected bubble gases.

It can be observed in the last two pictures of Figure 2b (arrow) and in other photographs that a barely visible small droplet is projected between two larger ones. These microscopic droplets are doubtlessly formed in the breakup of the jet. Similar phenomena have been photographed by other investigators in the breakup of a falling jet of water and in the breakup of raindrops. In other photographs (not published) large droplets were observed to strike the water surface and rebound with a much reduced diameter. These two phenomena, associated with the bursting of relatively large bubbles, indicate that these bubbles may also play an important role in the production of some smaller sized air-borne sea-salt nuclei.

Figures 1 & 2 show jets formed at the surface of tap water. Do the bursting of bubbles and the formation of the jet change appreciably in salt water or in water with a contaminated surface? The sequences in Figures 3 & 4 and in other photographs under various conditions indicate there is no significant change in the collapse of the cavity or formation and breakup of the jet. In sea water the only marked difference was that a much longer period of time elapsed between the arrival at the surface and the bursting of the bubble. For example, in Figure 3 the next bubble from the source has already arrived at the surface before the previous one has burst.

Compressed films of oleic acid on a sea water surface lower the surface tension and reduce the period of time spent by the bubble at the surface before bursting. This may be seen in Figure 4 where the bubble size is exactly the same as that in the previous figure.

One rather unusual event is seen in Figure 4b, where coalescence by collision is observed during upward bubble motion. This type of collision was observed on only 2 out of 8 sequences for this particular size bubble and surface condition and not in any of the other experiments under other conditions.

What is the effect of change in bubble size on the bursting mechanism? Figure 5 which is a surface view of a 0.4 mm. bubble in tap water, indicates that in general the picture is the same as that for 1.7 mm. bubbles. However, the time from initial burst to collapse of jet is considerably shorter than that of the larger bubbles. Measurements from photographs indicate that the total time is proportional to the bubble size. Another difference observed is that the larger droplets sometimes bounce once or twice when they hit the surface, whereas the small ones are not observed to do so.

A still smaller bubble size (0.2 mm.) is included in Figure 6. In salt water, these small bubbles do not burst upon arrival at the surface but tend to accumulate there in a patch, the bursting being relatively greatly delayed. Notice the rapidity with which the jets form and collapse. Figure 6b illustrates how a wave may initiate the bursting process. Three bubbles burst, two of them apparently triggered by the wave from the first.

Oleic acid applied to the surface again produced the effect of shortening the time required for the rupture of the bubble (Fig. 7).

Occasionally bubbles collide, forming a larger bubble by coalescence. This merging of bubbles is sometimes observed to produce oscillations which bring about the formation of other much smaller bubbles. An unusual jet formation and very large droplets observed with sea water having an oleic acid film, are shown in Figure 8b. At this point of our investigation it is not clear whether this is simply a vagary in the behavior of larger bubbles (Stuhlman, 1932) or whether it might be associated with the warming of the surface by the intense illumination used in these experiments.

Measurements of droplet sizes formed by all the different bubbles used in this investigation indicate that the average drop size is approximately one tenth the bubble size. Figure 1 shows the usual range of droplet size variation found from individual jets.

Woodcock (1952) gives a table of observed sea-salt nuclei and the corresponding droplet diameters at sea water concentrations. These data are reproduced on Table I together with a list of bubble diameters which would be expected to produce the corresponding droplets. The conclusion that may be drawn from Table I is that a bubble spectrum below 1.8 mm. diameter could produce the observed spectrum of air-borne sea-salt nuclei. This result is consistant with Stuhlman's (1932) observation that "for bubble diameters greater than 0.24 cm..... the ejection of the droplets was not of sufficient regularity to warrant quantitative interpretation".

III Summary of Conclusions

1. The bursting of a bubble at the air-water interface in sea water or fresh water produces droplets that are ejected upward to heights large compared to the bubble size. The mechanism by which the droplets are formed and given an initial vertical velocity is found to be a result of the formation and breakup of a jet of liquid which evolves from the collapsing bubble. The energy associated with the jet formation and breakup is principally derived from the collapse of the bubble cavity some time after initial rupture of the surface film.

2. The essential mechanism of bubble bursting and jet formation and breakup is not changed with bubble diameter over the range investigated (0.2 - 1.8 mm.). The total time required from rupture to decay of the jet was found to be proportional to the bubble size.

3. Bubbles bursting in sea water present essentially the same picture as those bursting in fresh water, with the exception that a much longer period of time is required to rupture the bubble in sea water. Oleic acid on the surface has no other observable effect than to reduce this time required to burst.

4. The droplets produced by bubbles up to 1.8 mm. in diameter (the upper limit for optimum droplet production) are of the order of 1/10 the bubble size. This range of bubble size corresponds to a salt nuclei weight range observed in the atmosphere.

5. Occasionally large bubbles are observed to produce much smaller droplets than those normally encountered. They appear simultaneously with the larger droplets. Also large droplets have been observed to reduce their mass upon rebound from the surface. These two methods suggest that large bubbles also are directly responsible for some of the lighter salt nuclei.

6. There is strong photographic evidence that the bursting

of small bubbles plays an important role in the production of particles of the size range commonly encountered in the atmosphere. The jet mechanism is the only method of droplet production which has been considered here. The rupture of the film on these small bubbles may produce other much smaller particles. This question could not be investigated by our methods.

IV Experimental Techniques

Two types of photographic observations were made in this investigation: (a) still photographs of very short exposure time (ca. 30 microsec.), taken at random during the bursting of a stream of bubbles; and (b) high speed motion pictures (ca. 3000 frames per sec.) of individual bubble bursts taken with an Eastman camera.

The photographic equipment for the still pictures consisted of an Argus C-3, 35 mm. camera with a Cinter 50 mm. lens on a 165 mm. lens extension tube. The magnification of the lens system is 3.3 diameters. The light source was a General Radio Strobolux, Model 648-A. This model Strobolux is rated for a duration of flash of less than 30 microseconds with a flashing rate up to 100 flashes per second.

The high speed pictures were made with an Eastman Highspeed camera type III, which used 100 ft. rolls of 16 mm. film. The lens system for this camera was a Kodak Anastigmat f2.7, 63 mm. lens and a 105 mm. lens extension. The effective magnification was 1.7 diameters. A photospot (No. RSP2) lamp, at close range, was used as a light source. The Eastman Highspeed has a frame exposure time of one fifth the picture cycle, and, since the average speed was near 3000 frames per second, the average exposure was about 65 microseconds.

In both the stroboscopic and high speed photographs, back lighting was used. Light reflected by a mirror from the light source was directed through the bubble into the lens as indicated in Figure 9. It was found that this method produced enough illumination to enable the use of a small aperture with both cameras.

The bubbles were formed at the end of a drawn out glass capillary placed 10-20 mm. below the liquid surface. The bubble size was varied by changing either the tip size or air pressure. The liquids used in this investigation were tap water, sea water, and sea water with the surface modified with a compressed film of oleic acid. The fresh and sea water surfaces were flushed prior to photographing and free from known surface contamination. The bulk liquid temperature was in general at the ambient air temperature which varied from 21°C to 25°C.

The horizontal photographs of the bubbles bursting at the surface were taken through a glass microscope slide that had been placed in the glass jar that contained the bubble source. The inner surface had been previously coated with General Electric Dri-film to reduce the meniscus effect on the glass.

V Acknowledgments

The authors wish to acknowledge the valuable comments and advice of A. H. Woodcock and C. H. Keith of the Woods Hole Oceanographic Institution and wish to thank Dr. E. Swift, Jr. of the Naval Ordnance Laboratory for the technical assistance which made this investigation possible.

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Table I

Diameters of bubbles which would produce sea-salt particles of sizes observed in the atmoshpere.

Weight of sea-salt nucleus (micro-micro gms.)	Diameter of sea water droplet from which nucleus is derived. (microns)	Approx. diameter of bubble which would produce corresponding droplet (microns)
1	3.8	40
10	8.1	80
10^2	17.4	170
10^3	37.6	380
10^4	91.0	910
10^5	174.0	1700

Figure 1. Still photographs of 1.0 mm diameter bubble bursting in fresh water with a clean surface. (Sequence of stills is based on comparison with high speed motion picutres). Angle of view 5 to 10° above horizontal.

a. Bubble approaching surface
b. Just after rupture of film
c. Initial rise of jet
d, e, f, g. Projection of droplets and decay of jet.

Exposure time ca. 30 microseconds. Time intervals between pictures uncertain.

Figure 2. High speed motion pictures of 1.7 mm diameter bubbles bursting in fresh water with clean surface. Angle of view horizontal, through wall formed by glass microscope slide.

a. Camera speed: 3340 frames/sec.
b. Camera speed: 3000 frames/sec.

Note barely resolvable droplet indicated by arrow.

Figure 3. High speed motion pictures of 0.7 mm diameter bubbles bursting in sea water with clean surface. Angle of view: horizontal. Meniscus at wall obscures lower part of jet. Camera speed: 3300 frames/sec.

Figure 4. High speed motion pictures of 0.7 mm diameter bubbles bursting in sea water with surface film of oleic acid. Angle view: horizontal. Meniscus at wall obscures lower part of jet.

a. Camera speed: 3150 frames/sec.
b. Camera speed: 3300 frames/sec.

Note coalescence of droplets by collision in last four frames.

Figure 5. High speed motion pictures of 0.4 mm diameter bubble bursting in fresh water with clean surface. Note wave propagation after burst. Angle of view: 18° above horizontal. Camera speed: 3260 frames/sec.

Figure 6. High speed motion pictures of 0.2 mm diameter bubbles bursting in sea water with clean surface. Bubbles form patch at surface and break randomly, waves from one burst apparently triggering other. Angle of view: 18° above horizontal. Camera speed: 3300 frames/sec.

Figure 7. High speed motion pictures of 0.2 mm diameter bubbles bursting in sea water with surface film of oleic acid. Bubbles burst as they strike surface without forming patch as in Figure 8. Angle of view: 18° above horizontal. Camera speed: 3000 frames/sec.

Figure 8. High speed motion pictures of 1.3 mm diameter bubbles bursting in sea water with surface film of oleic acid. Angle of view: 10° above horizontal.

a. Camera speed: 2600 frames/sec.

b. Unusual burst with thick, low jet and large droplet. Camera speed: 3000 frames/sec.

Figure 9. Schematic diagram of photographic equipment and bubble source.

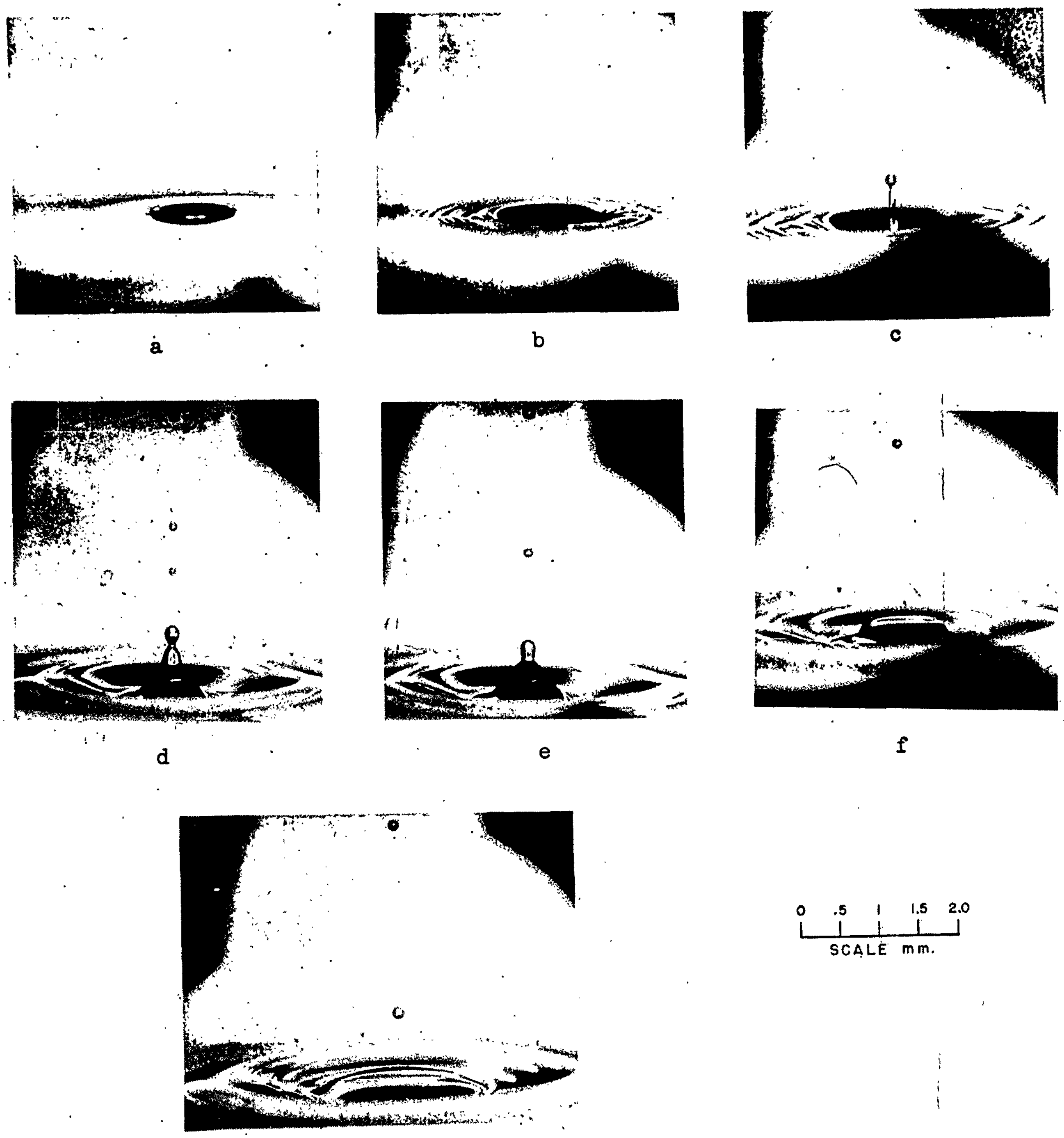


Fig. 1 Still photographs of 1.0 mm diameter bubble bursting in fresh water with a clean surface. (Sequence of stills is based on comparison with high speed motion pictures). Angle of view: 5 to 10° above horizontal.

a. Bubble approaching surface.
b. Just after rupture of film.
c. Initial rise of jet.
d, e, f, g. Projection of droplets and decay of jet.

Exposure time ca. 30 microseconds. Time intervals between pictures uncertain.

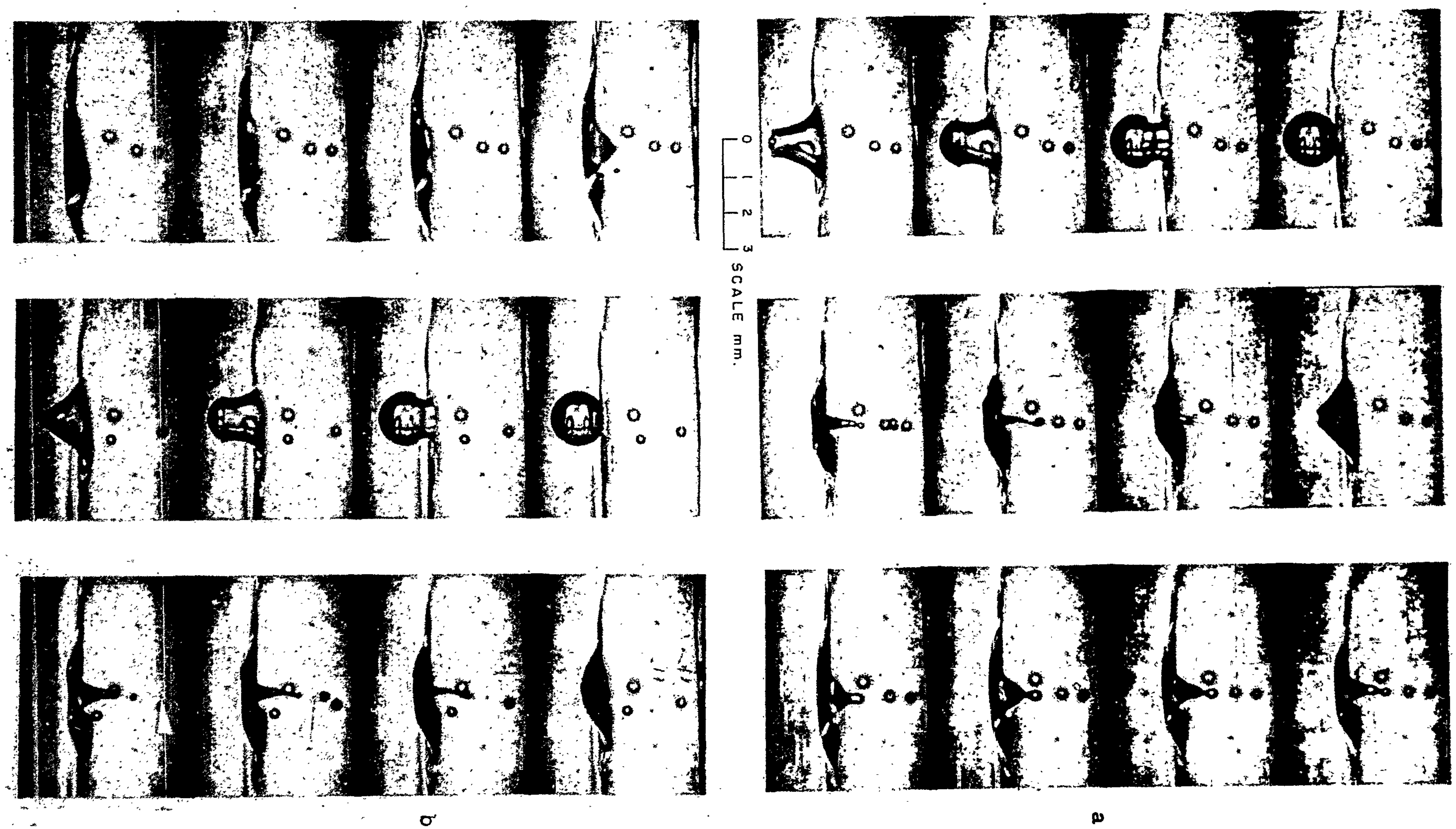


Fig. 2 High speed motion pictures of 1.7 mm diameter bubbles bursting in fresh water with clean surface.
Angle of view: horizontal, through wall formed by glass microscope slide.

a. Camera speed: 3340 frames/sec.
b. Camera speed: 3000 frames/sec.

Note barely resolvable droplet indicated by arrow.

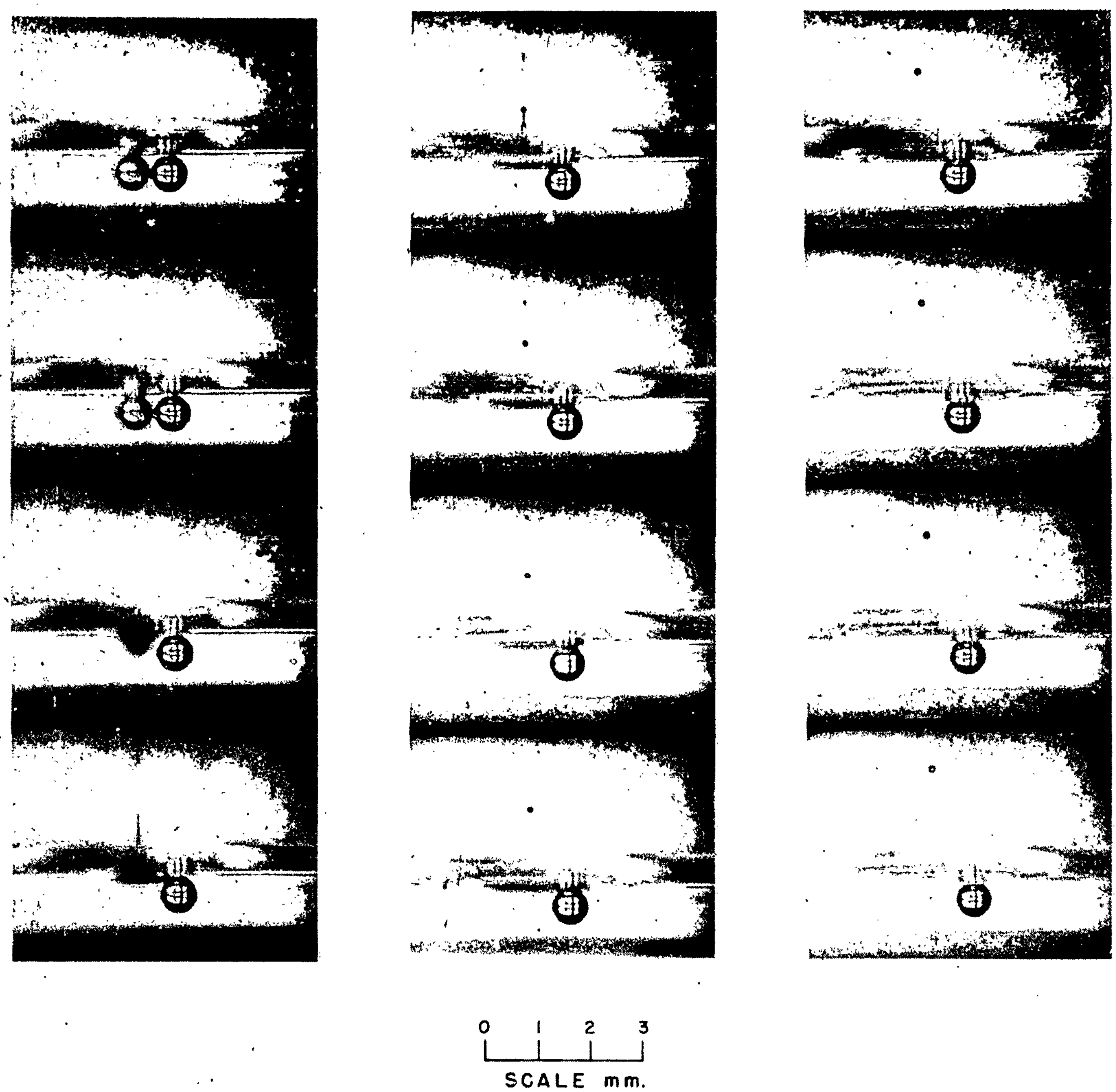


Fig. 3 High speed motion pictures of 0.7 mm diameter bubbles bursting in sea water with clean surface. Angle of view: horizontal. Meniscus at wall obscures lower part of jet. Camera speed: 3300 frames/sec.

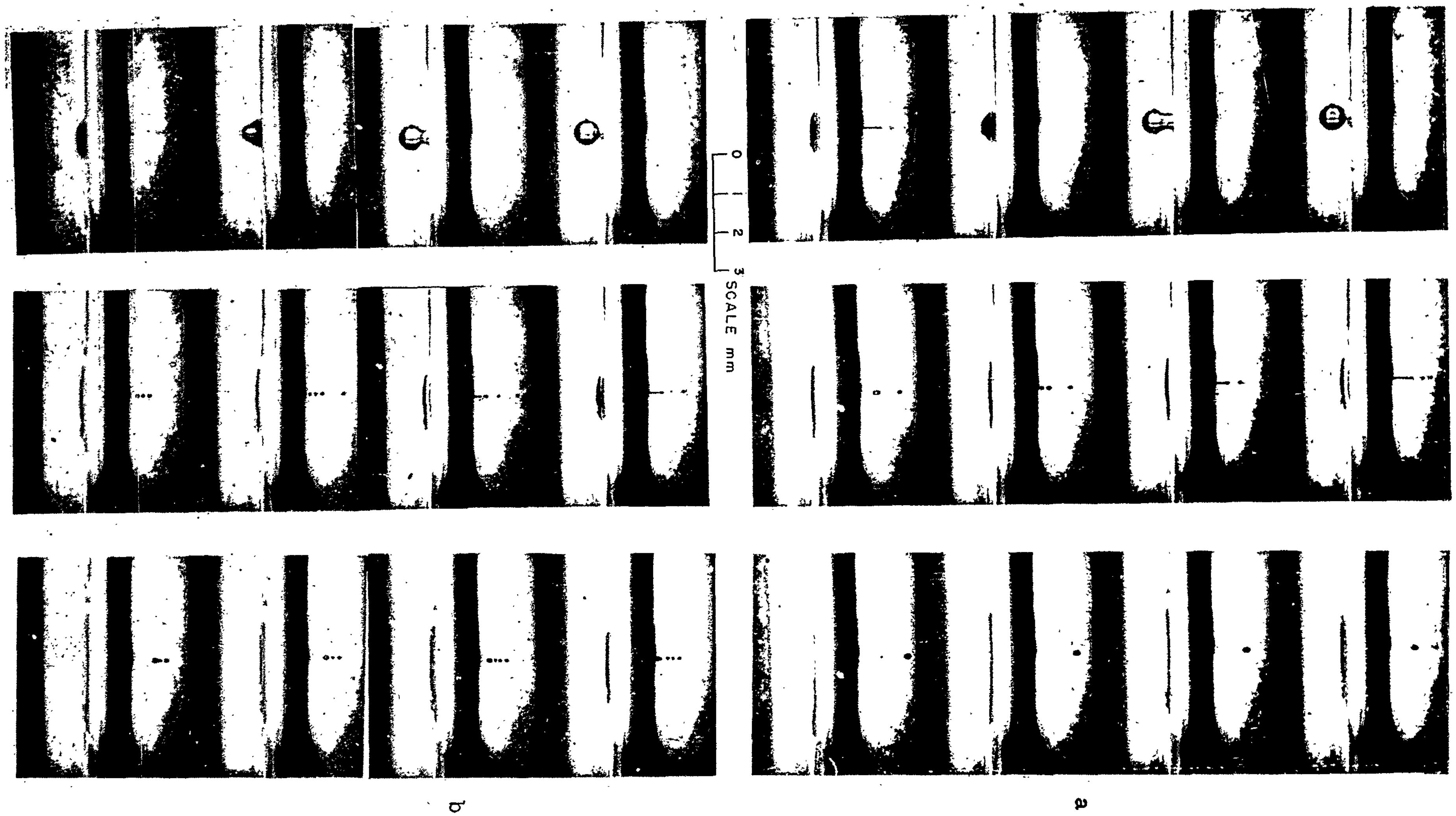


Fig. 4 High speed motion pictures of 0.7 mm diameter bubbles bursting in sea water with surface film of oleic acid. Angle of view: horizontal. Meniscus at wall obscures lower part of jet.

a. Camera speed: 3150 frames/sec.

b. Camera speed: 3300 frames/sec.

Note coalescence of droplets by collision in last four frames.

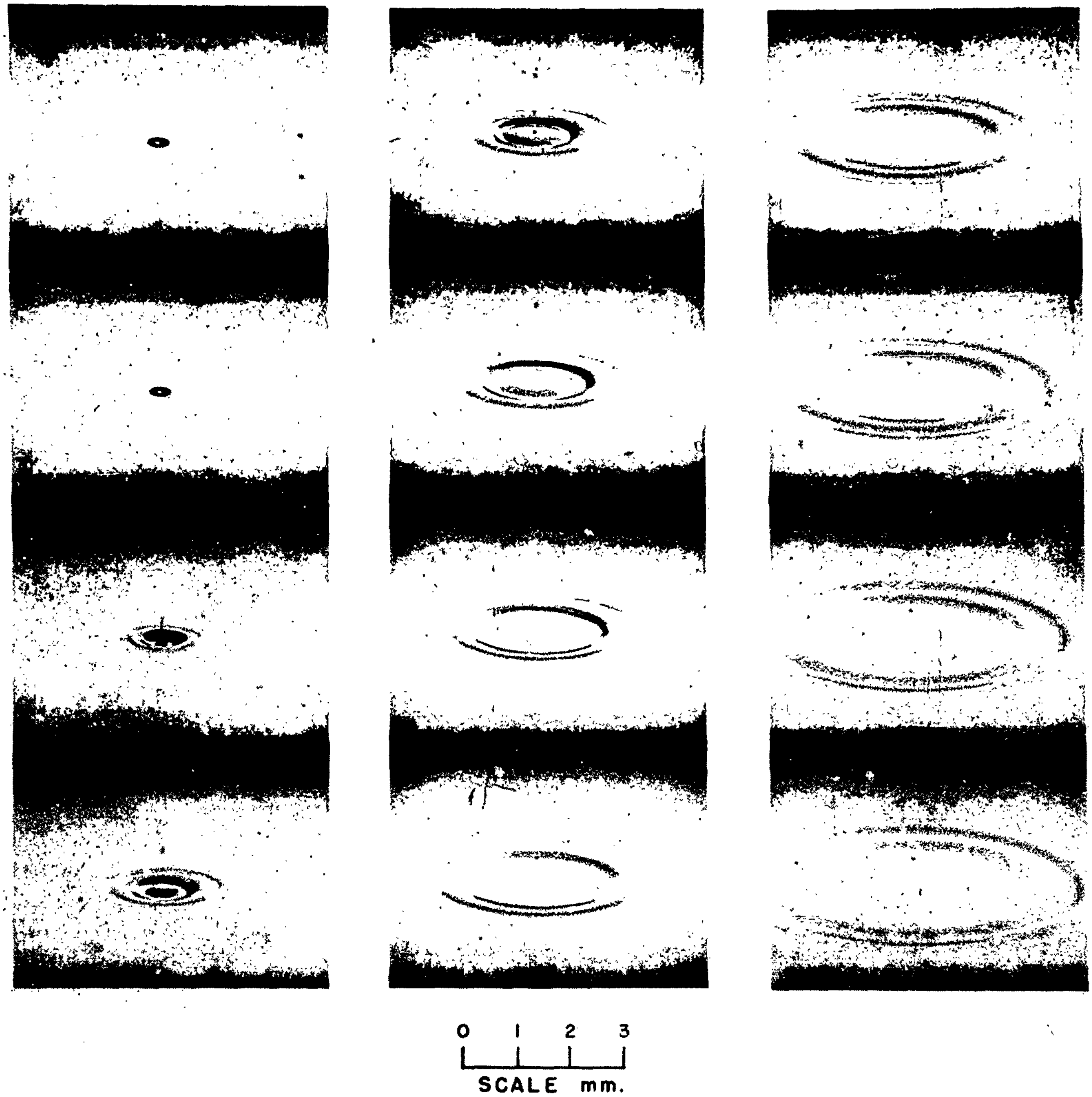


Fig. 5 High speed motion pictures of 0.4 mm diameter bubble bursting in fresh water with clean surface. Note wave propagation after burst. Angle of view: 18° above horizontal. Camera speed: 3260 frames/sec.

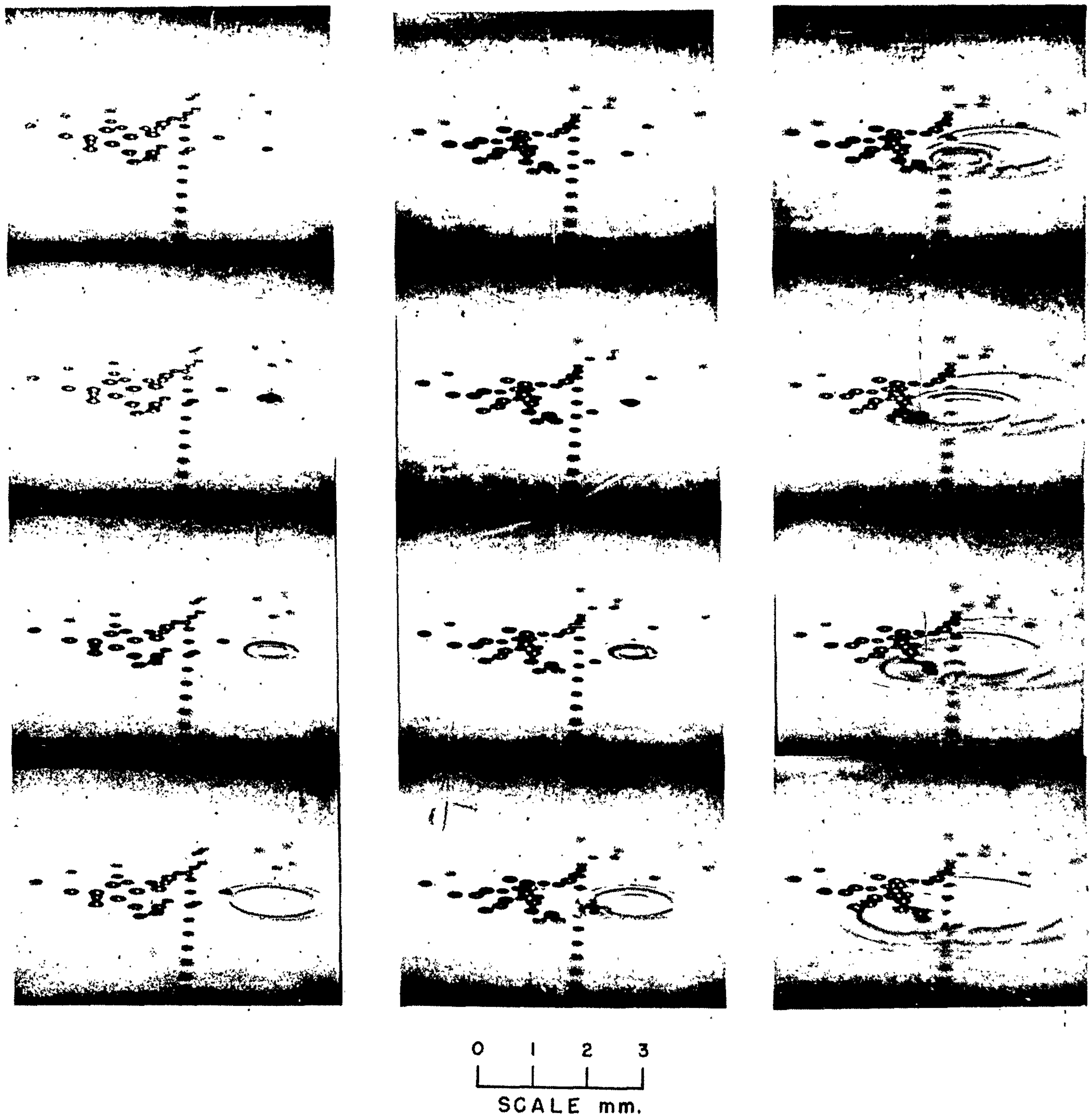


Fig. 6 High speed motion pictures of 0.2 mm diameter bubbles bursting in sea water with clean surface. Bubbles form patch at surface and break randomly, waves from one burst apparently triggering others. Angle of view: 18° above horizontal. Camera speed: 3300 frames/sec.

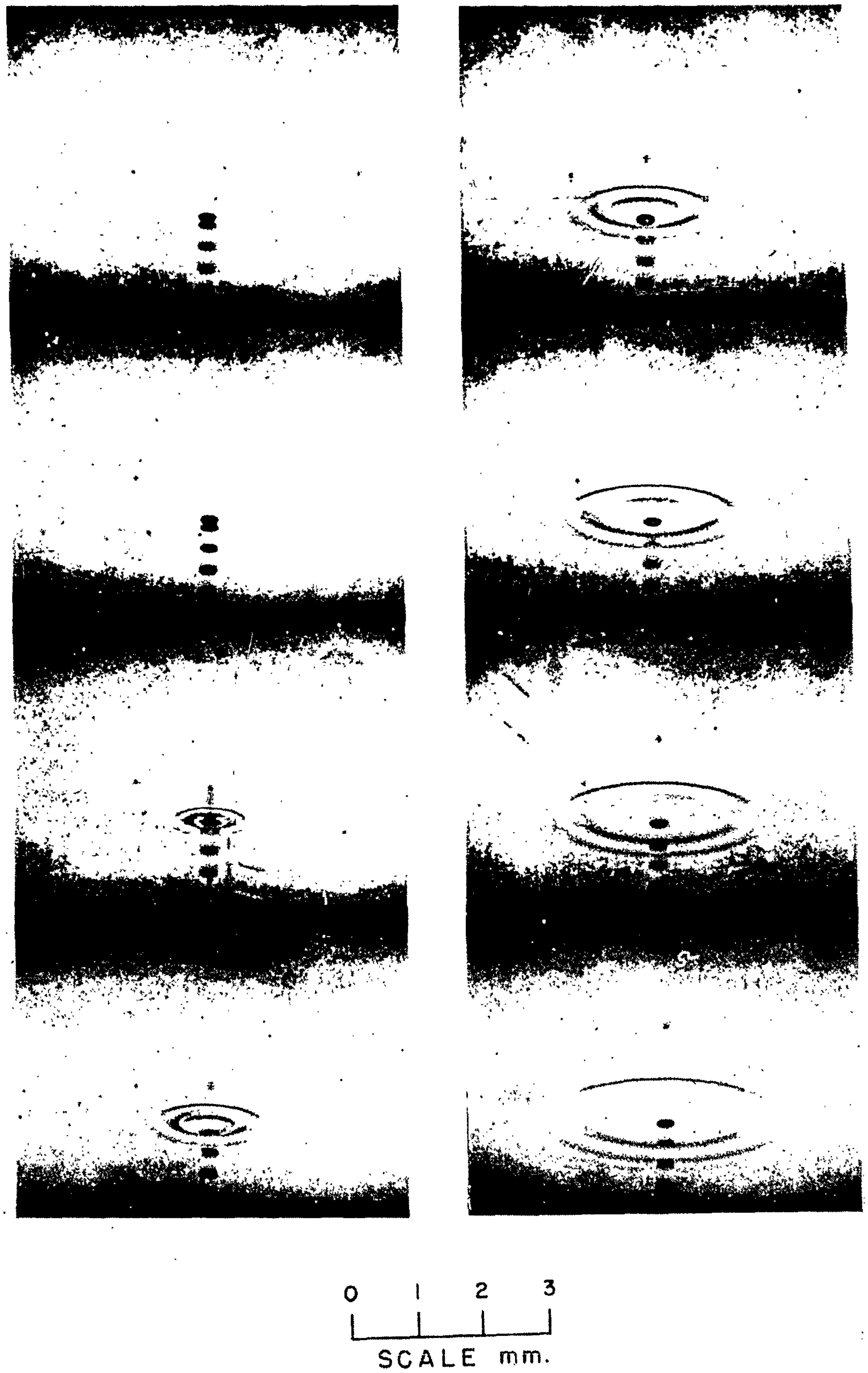
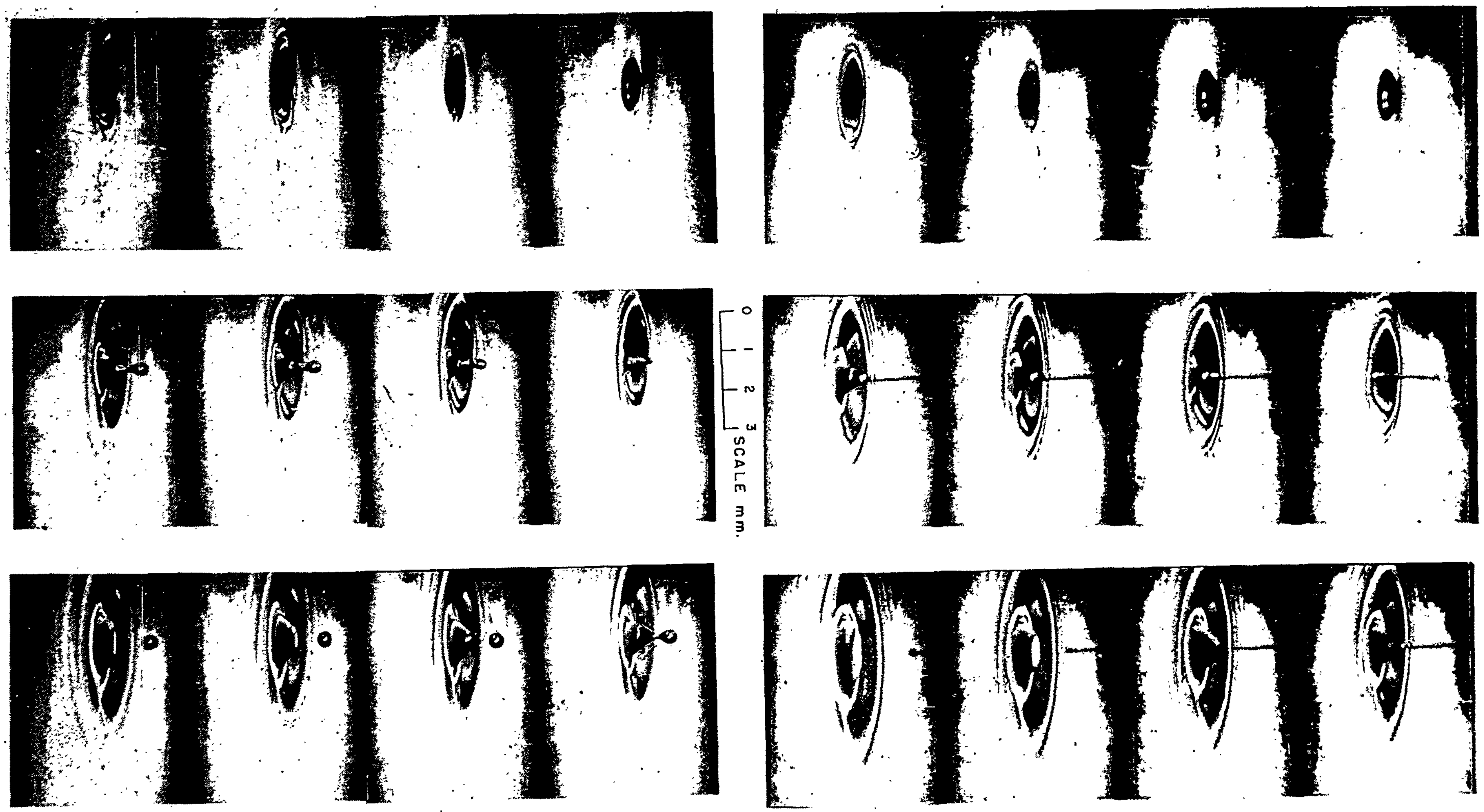


Fig. 7 High speed motion pictures of 0.2 mm diameter bubbles bursting in sea water with surface film of oleic acid. Bubbles burst as they strike surface without forming patch as in Figure 8. Angle of view: 18° above horizontal. Camera speed: 3000 frames/sec.



b a

Fig. 8 High speed motion pictures of 1.3 mm diameter bubbles bursting in sea water with surface film of oleic acid. Angle of view: 10° above horizontal.

a. Camera speed: 2600 frames/sec.

b. Unusual burst with thick, low jet and large droplet. Camera speed: 3000 frames/sec.

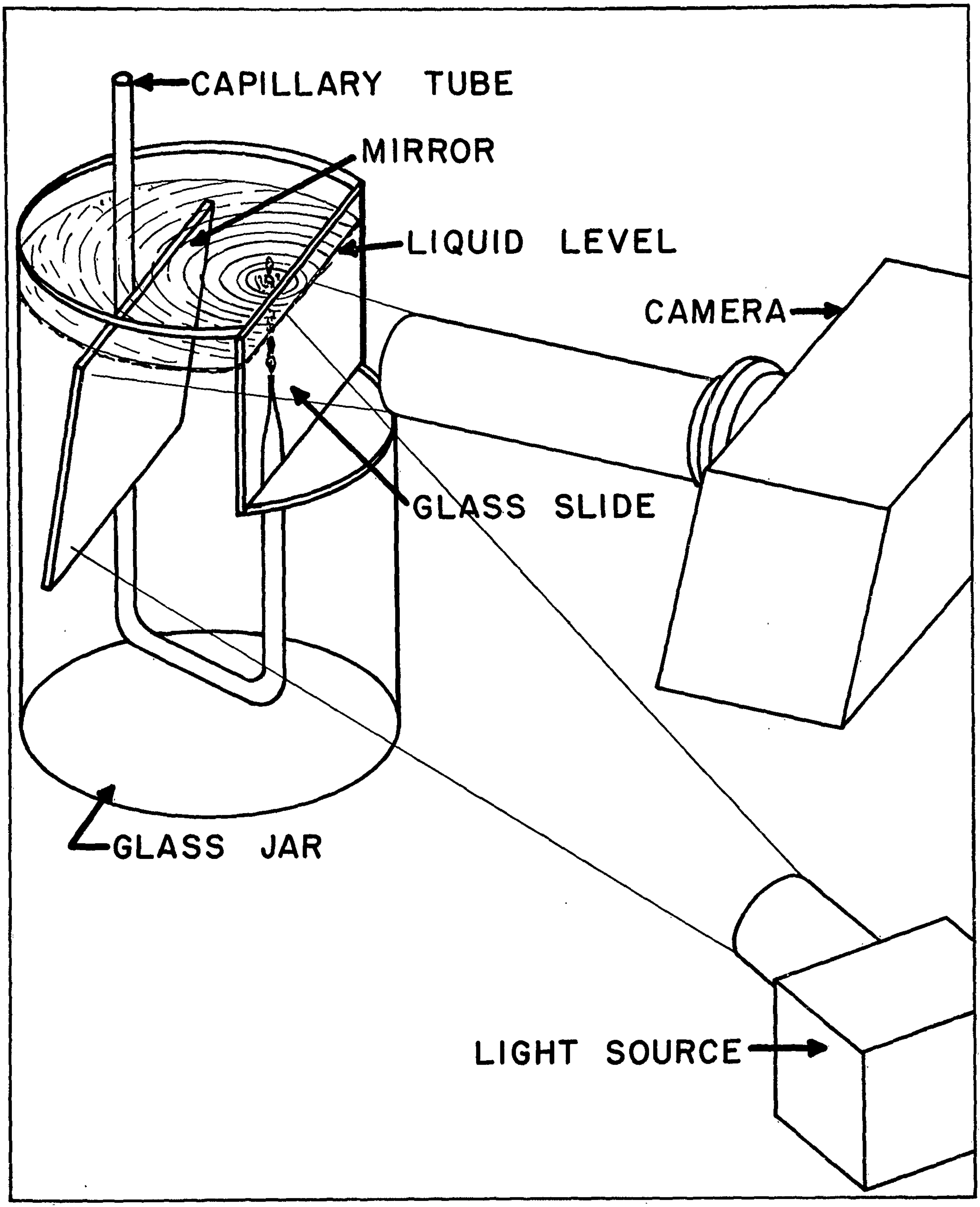


Fig. 9 Schematic diagram of photographic equipment and bubble source.